Discussions Notes from

Advanced Concept ARO 200 Centrifuge Workshop

US Army Corps of Engineers

Engineer Research and Development Center - Vicksburg, MS

January 31 – February 1, 2001

A. Session on Hydraulics, Coastal Systems and Sustainment Engineering -- Wednesday, January 31

Panelists:

Introductory Lecturer:	Dr. Ryan Phillips, Director of Geotechnical Engineering Centrifuge, Centre for Cold Oceans Resources Engineering, Memorial University, Newfoundland, Canada
Moderator:	Dr. Edward Clukey, BP-Amoco
Co- Panelist:	Dr. Stacey Howington, Coastal Hydraulics Lab, ERDC
Discussion Notes By:	Tony King, CCORE

Q (Tom Zimmie): What is a gravity knob?

A (Stacy Howington): The term "gravity knob" refers to changing acceleration through the use of the centrifuge, leaving other variables such as capillary forces the same, and observing the results.

Q (Deborah Goodings) With respect to the disturbance of sediments seen during wave-induced liquefaction, this must be similar to the behaviour that is seen while capping sediments. Gravel caps have been used as a capping material, but it has later been observed that the gravel cap ends up at the bottom of the sediment. It seems like having nothing is better than using a gravel cap.

A (Ryan Phillips): A gravel cap is better than nothing, however a wider cap is better in terms of stability.

Q: Is the ice used for ice/structure modelling grown in the centrifuge?

A (Ryan Phillips): When modelling structure interaction with an ice sheet the ice must be grown in flight. The surface of a free water surface in the centrifuge actually has some degree of curvature, which is a function of the radius of the centrifuge. The ice sheet must be grown in flight to accommodate this curvature.

Q (Bill Marcuson): Has any work been done on the dredging of rock? For example, considering the strength of the rock, the influence of fracturing and the effort required to dredge it?

A (Ryan Phillips): None that we are aware of.

Q (Kevin Stone): What is the influence of crystal size on the ice sheets grown in the centrifuge on the behaviour observed?

A (Ryan Phillips): First, not all the ice used for ice modelling is grown in-flight. When using ice rubble, the ice is grown at 1-g, crushed and sorted to get the right size gradation and placed in the strongbox. For ice grown in-flight, at this point there is insufficient knowledge on the topic to give any definite answer. The evidence to date, in terms of behaviour observed in the centrifuge, indicates that the technique is valid.

Q: Has there been modelling of the dynamic response of the behaviour of coffer dams and similar structures in the offshore setting?

A: Work has been done on dam response to earthquakes and other, similar situations.

Q: There was some mention of fracture mechanics and its implications for centrifuge modelling. Could you please elaborate?

A (Ryan Phillips): If the modelling of models technique works, then it is safe to say that the application of centrifuge modelling for a particular situation is valid. However, if it is a situation where fracture mechanics may govern behaviour, and the modelling of models does not work, then this would be an indication that perhaps this is the case. For fractures, other factors, such as the length of cracks control the behaviour, rather than weight.

Q: Could you elaborate on the use of electrical resistivity tomography for monitoring the movement of contaminants during centrifuge modelling?

A (Stacy Howington): The electrodes were spaced around the wells at various elevations at 20-30° intervals. Obtaining measurements is not difficult; solving the inverse problem to define the movement of the contaminant is the difficult part. Problems occur when the contaminant is discontinuous – for example when fingering occurs.

Q (Tom Zimmie): Measuring the movement of contaminants is a problem – especially when multiple contaminants are considered. We have considered using a cat scan, and have priced a system for 150k, however there are no guarantees whether it would stand up to use in the centrifuge. Other technologies such as MRI and GPR are also possibilities. Any comments?

A (Ryan Phillips): The pharmaceutical industry has developed a variety of sensors that could certainly be adapted for use in the centrifuge. There are other possibilities, depending on the process being modeled. For example, the absorption of Gamma rays has been used to measure density changes in clay during consolidation.

Q: What aspect of centrifuge modelling is most in need of improvement?

A (Edward Clukey): The measurement of *in situ* soil/sample properties is a challenge. Everyone is using Speswhite kaolin clay because the properties are well known. Still, cone tip resistances can be difficult to interpret. In the field, shear vanes are used in collaboration with cone tip resistances to aid in interpretation. The type of centrifuge program is also a consideration. If an "application" type centrifuge program is being conducted then you are not necessarily interested in all the soil properties – the overall goal of the program might simply be to generate some type of load/displacement curve for design purposes.

Q: It seems everyone has to start from scratch when developing a centrifuge test. Wouldn't it be more efficient to share techniques?

A (Ryan Phillips): Occasionally, there can be problems with confidentially requirements that can be an impediment. Often, there are sufficient details in publications and associated thesis documents that give the required details. I have never experienced a problem when approaching other centrifuge centers regarding centrifuge techniques. There is a useful link on the ISSMGE website which gives access to a comprehensive list of centrifuge publications. This link will be included as part of the proceedings of this workshop.

Q: Which parameters are considered most important to control when designing a centrifuge experiment?

A: That varies from project to project. It is necessary to focus in on the pertinent parameters.

Q (Deborah Goodings): What are the requirements of the Army with respect to hydraulic and coastal engineering?

A (Bill Marcuson): We have identified research requirements in areas such as beach erosion and protection, terrorist threat protection, flooding protection and reduction of flooding damage. Also of interest are unburied, unexploded armaments in the coastal zone and mine fields.

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B. Session on Geoenvironmental Engineering -- Thursday, February 1

Panelists:

Introductory Lecturer:	Prof. Patricia J. Culligan, Massachusetts Institute of Technology
Moderator:	Prof. Kevin Stone, University of Brighton
Co- Panelist:	Dr. Tommy Myers, Environmental Lab, ERDC
Discussion Notes by:	Catalina Marulanda, MIT

Prof. Culligan

The title of Prof. Culligan's presentation was "Use of Centrifuge Testing in Geo-Environmental Engineering".

- A general background on centrifuge testing was reviewed, including the advantages of the method in modeling geo-environmental problems, its applications in this area, and the governing scaling laws.

- Some examples of centrifuge modeling work of geo-environmental problems were presented, starting with a study of "LNAPL Transport in Unsaturated Soil" conducted by H. Nikajima, M. Mariño and B. Kutter, at the University of California at Davis. This research project consisted of studying the transport of a volume of LNAPL leaking from an underground drum buried in the vadose zone. Centrifuge experiments were conducted to track the movement of the LNAPL, which flowed downward through the unsaturated soil and accumulated at the top of the capillary fringe. Results of experiments were presented, along with results of computer simulations based on the experimental work. Good agreement between the experiments and computer simulations were observed.

- The example following was a study of "DNAPL Migration in a Saturated Layered System" directed by K. Soga at the Cambridge University Engineering Department, U.K. This study tracked the flow of DNAPL through both inclined and horizontal layered deposits. The characteristic shapes of the resulting pools of DNAPL at steady state were presented and compared with predictions from a numerical model. Again, good agreement was noted between the experimental data and numerical predictions.

- A study of "DNAPL Migration in Vertical Fractures" was presented next. This study is being conducted by L. Levy, P. Culligan, and J. Germaine at MIT. This research aims at describing the flow of DNAPL through fractured networks, a problem that has been ranked by the National Research Council as one of the hardest environmental remediation challenges to resolve. Centrifuge modeling of the problem has involved the use of capillary tubes of square and circular cross sections to represent individual fractures. These tubes are subjected to increasing g-levels, and the characteristics of DNAPL invasion and infiltration are evaluated from the test data. Experimental results have been used to validate predictions from a model developed during the study, which predicts DNAPL exit velocity from fracture geometry and DNAPL fluid properties alone. Potential applications of these findings can be foreseen in the design of hydraulic flushing systems for the remediation of DNAPL contaminated fractures.

- The following example considered the disposal of dredged material, a study conducted by L. Potter and C. Savvidou, in the Cambridge University Engineering Department, U.K. The issue considered in the study was that of disposing contaminated dredged material in ditches underwater, and the capping of this material to avoid the re-suspension and migration of contaminants. Centrifuge testing was conducted to evaluate the pore pressure dissipation in the material with time and the corresponding increase in its strength, necessary to support the designed cap. The study also considered the migration of contaminants through the consolidated dredged material with time.

- A study on the "Efficiency of In-situ Air Sparging (IAS)", conducted at MIT by C. Marulanda and P. Culligan was presented next. IAS is a remediation technology applicable to volatile compounds, which consists of injecting pressurized gas into the ground, below the water table. As the gas flows upward through the soil column it volatilizes the contaminants it encounters, which become incorporated into the advective gas phase and can thus be treated at the ground surface. The study in question utilizes a see-through porous medium to evaluate and optimize the patterns of air flow through the soil, in order to maximize the area affected by the injected gas. Air flow patterns have been found to vary with g-level, and more specifically with the ratio between buoyant and capillary forces. Potential applications of these results include the development of design guidelines that will increase the effectiveness of the remediation technology.

- The last example presented was that of "Centrifuge Testing of GCL-Leachate Compatibility", a study conducted by B. Cooke and A. Cole at the University of New Brunswick, in Canada. Centrifuge testing was performed on samples of a Geo-synthetic Clay Liner (GCL), subjected to varying g-levels in order to determine the effect of increasing effective stresses on their hydraulic conductivity. As expected, results show that (i) hydraulic conductivity decreases with increasing stress level, and (ii) leachate permeation influences the integrity of the GCL.

- In summary, it was shown that a wide variety of Geoenvironmental problems can be addressed by centrifuge testing. The most useful contributions of centrifuge testing to the overall modeling community might be in the following areas:

- Assistance in the development, validation, and calibration of numerical models
- Investigation of fundamental behavior

- In the future, modeling of site-specific problems might be used to assist with the screening of alternative remediation technologies and risk assessment.

Prof. Stone

Professor Stone presented a case study of tailings management in the Booddington Gold Mine in Western Australia, which illustrates the use of centrifuge as a tool to predict field behavior.

- Centrifuge modeling was used as a testing tool to: 1) predict the increase in strength of the tailings with time; 2) estimate discharge quantities of the contaminants; and 3) predict the settlement rate, and consequently the rate of filling, of the site.

- The methodology of the study consisted in:
  - evaluating field data through the use of laboratory tests
  - use of physical modeling (centrifuge experiments were calibrated with field data)
  - use of numerical analysis

- In order to make predictions on the behavior of the tailings it was necessary to replicate, in the centrifuge, the manner in which the impoundment had been built over the years. The first part of the experiments replicated the filling behavior of the dam up to the date of testing, while the second part of the tests projected and predicted the future behavior of the deposits (including future rates of filling).

- It was necessary to replicate field-filling procedures during sample preparation, in order to simulate the progressive consolidation of the layers of tailings during filling of the impoundment. Filling of the centrifuge sample was therefore not done continuously, and the centrifuge was stopped after each layer had been deposited. After the field level of tailings had been reached in the model, filling was continued using the planned rates, and predictions were made of the behavior of the impoundment after 19 years.

- The numerical model was calibrated using centrifuge data, which enabled predictions of tailing behavior under different scenarios to be made.

- Prof. Stone concluded that the case study illustrated the integrated research process that takes place by combining: 1) field data; 2) physical modeling; 3) numerical modeling; and 4) industry support.

- Suggested recent and future developments included:

- a technique which has been already used, namely the co-disposal in layers (in-flight mixing and deposition)
- simulation of evaporation and crusting at the surface
- foundation performance of crusted soils
- physical an numerical modeling of intermediate soils

- In closing, Prof. Stone suggested the use of micro-fractured chalk as a medium to model fractured rock. Fractured chalk offers the possibility of using a real material to model fractured networks, and could be used in the study of contaminated fracture remediation.

Dr. Myers

Dr. Myers intervention consisted of general comments regarding centrifuge modeling from the point of view of the non-centrifuge modeling community.

- There is great interest and optimism about the bold possibilities of centrifuge modeling, but centrifuge users need to be cautious when presenting their work to other scientists in order to avoid misinterpretations. There is a difference in terminology amongst the scientific community that can lead to misunderstandings.

- There is an overall agreement in the scientific community that processes affected by gravity forces can be accurately modeled in the centrifuge. It is also accepted that the centrifuge provides a unique tool for modeling these physical processes. However, caution needs to be used when using centrifuge modeling in areas such as contaminant transport in porous media. In these types of scenarios, non-conservative processes such as adsorption and absorption take place, which cannot be simulated in the centrifuge.

- Physical processes like diffusion, for example, are not necessarily best modeled in the centrifuge. The gravity term is not present in the equations describing diffusive processes and, thus, the use of higher g-levels to model these processes might not be appropriate.

- Modeling of non-reactive materials and compounds can be done in certain cases, but non-conservative reactions do not scale.

A panel discussion moderated by Prof. Stone followed the intervention by Dr. Myers. Comments and questions have been transcribed, specifying the name of the speaker, when available.

- *Question:* What was the scale factor used for the experiments of the Australian tailings? How long did the experiments last?

Prof. Stone: The scaling factor was 100-*g*. The first stage of the experiments lasted approximately 20 hours, after which the centrifuge was stopped and the test was suspended overnight. The following morning, the sample was brought back to the same state of effective stress as it was at the end of consolidation, and the second stage of the experiments was conducted.

Q: Was swelling of the sample a problem following stress release? *(Prof. Goodings)*

Prof. Stone: A certain amount of swelling does occur and was taken into account in the analysis. However, the behavior of the sample is not affected as long as it is taken back to the same level of effective stress.

- *Q:* What is the influence of the smooth glass tubes on the modeled behavior of flow through fracture media? How much does the roughness of natural fractures affect flow? (*Prof. Kutter*)

  Prof. Culligan: The relative roughness/smoothness of the system greatly affects the characteristics of the flow, and this is taken into account by the wettability of the fluid, or the angle of contact of the pore fluid and the fracture.

- *Q:* Has modeling of models been done for the air sparging experiments? What is the effect of the varying stress gradients at increasing g-levels?

  Prof. Culligan: The principle of modeling of models has been applied and is valid for air sparging experiments performed at lower g-levels. It is not applicable to experiments performed at high g-levels.

- *Prof. Culligan discussing the values of permeability used in centrifuge modeling in response to a comment made by Dr. W. Marcuson:* Similitude between model and prototype in centrifuge modeling can only be claimed if inertial forces in the model are not important. The Reynolds number, which represents the ratio between inertial and viscous forces, is an important parameter in centrifuge modeling. If inertial forces become a factor of concern and the Reynolds number increases, fluid properties need to be modified (*i.e.* fluids need to be replaced) in order to maintain similitude. The use of fluids with varying properties is commonly used in earthquake modeling, for example, but might be difficult to implement when dealing with problems of fluid transport.

- *Q:* How well has centrifuge modeling been marketed amongst the non-centrifuge modeling and the engineering community?

  Dr. Myers: The level of exposure of the non-centrifuge community to centrifuge modeling varies depending on the field. However, there needs to be awareness of the difference in language between the various communities, in order to avoid misunderstandings and general communication problems.

- *Q:* Can corrosion be modeled in the centrifuge?

  Prof. Culligan: It will probably be very difficult to replicate bacterial communities in a centrifuge.

  Dr. Myers: Chemical reactions that do not contain a gravity term in their theoretical formulation will not be accelerated in the centrifuge, and therefore cannot be accurately modeled by centrifuge testing.

  Comment from Dr. R. Smith: Modeling of chemical interactions in the centrifuge can be done in cases in which fluid flow through a medium triggers a certain chemical reaction. In these cases modeling is based on the principle of altering chemical rates, which is achieved by increasing the gravity level and causing a gradual decrease of the hydraulic conductivity of the medium. The relative amount of fluid flow through the medium determines the rate of the chemical reaction being modeled. In these types of cases however, it is important to consider to which extent the pore structure of the medium remains comparable at increasing g-levels, and what the consequences of structural changes are on the modeled phenomenon.

  Prof. Kutter: The coupling between the different processes that takes place in the centrifuge also takes places in the field, and therefore if a given model applies to the centrifuge it will also apply to the field.

  Dr. Myer: Fundamental disagreement with Prof. Kutter's comment. The phenomena observed in the centrifuge are not representative of field situations, because equilibrium conditions, as they are defined in most theoretical derivations, are not met during processes in which advection is increased to the levels seen in centrifuge modeling. Centrifuge experiments of tracers breaking through landfill caps, for example, show that equilibrium does not occur prior to breakthrough.

  Dr. R. Smith: Kinetic processes in the laboratory always occur at faster rates than those observed in the field, because it is not possible, in the laboratory, to control all of the variables and the heterogeneities that exist in the field. It is very difficult, even at 1-*g*, to control both the process and the control rates, and therefore perfect scaling will probably not occur in the centrifuge. Centrifuge modeling however, is very useful in identifying the mechanisms that are taking place in a given situation.

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C. Session on Extreme Environments, Survivability, and Transportation Geotechnics -- Thursday, February 1

Panelists:

Introductory Lecturer:	Prof. Deborah J. Goodings, University of Maryland
Moderator:	Dr. Stephen Ketcham, US Army Cold Regions Research and Engineering Lab, ERDC, NH
Co- Panelist:	Dr. James Gran, SRI
Discussion Notes by:	Silas Nichols, University of Maryland

Question from Dr. Ketcham:
What other topics in Extreme Environments do researchers know of that have not been covered here?

Response from Dr. Clukey:
He is aware of research regarding the movement of salt in the Gulf of Mexico creating slope stability issues in the seabed. Because there are no earthquake worries and the seabed is too deep to be affected by waves, it is believed that salt is the primary culprit. *In response to a question regarding how the salt got down there* - Dr. Clucky replied that it is the result of rising sea level forcing the salt down onto the seabed in deep waters.

Response from Dr. Gran:
He is aware of work in dynamic effects on rock strength. In competent rock, the in-situ stresses created by dynamic cratering processes is significant. Jointing is critical and observations may be peculiar to the construction process for modeling. As the material strength increases, gravity of the rock mass has greater impact.

Response from Dr. Goodings:
With regard to hot extremes, she is aware of research on tunnel fires as a structural problem. That is, how the soil is affected by extreme heat and how tunnel stability is affected. This work has not been developed on the centrifuge.

Response from Dr. Clukey:
He is also aware of research on hydrates forming in pipelines. The solution has been to insulate pipes, however it may be productive to consider burying pipes for insulation purposes.

Question from Dr. Schaminée:
In Holland and in Australia, soft ground tunnelling has become a big topic. Is this also an issue here (in North America)?

Response from Dr. Goodings:
She is aware of work on soft ground tunneling in Great Britain. She said there were references that she could identify for him.

Response from Dr. Ryan:
Commented that this workshop was really about looking at new and innovative techniques. Tunneling is more of a classical application.

Response to Dr. Ryan from Dr. Schaminée:
It may be, but there are still a lot of questions unanswered.

Question from Dr. Ryan directed toward Dr. Culligan:
He wondered whether there was any research in pollution migration -- specifically, hazardous materials and the effects of heat generation on soils and sea beds.

Response from Dr. Culligan:
She commented that there was research in related areas. However, it is politically unfeasible at this time to consider depositing heat generating waste (radioactive) in sea beds.

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D. Session on the Future of Centrifuge Modelling -- Thursday, February 1

Lecturer:	Prof. Hon-Yim Ko - University of Colorado
Moderator:	Dr. Ryan Phillips - Center for Cold Oceans Research Engineeering
Co-Panelists:	Prof. Ricardo Dobry, Renselaer Polytechnic Institute Prof. Patricia Culligan, MIT Prof. Deborah Goodings, University of Maryland
Discussion notes by:	Silas Nichols, University of Maryland

Comment by Dr. Clukey:
Centrifuge modeling should take the step toward use as a design tool. However, the use of centrifuge modeling in verifying foundation designs requires a look at developing standards and codes for modes of testing. Design jobs are going to be bid, and independent labs must be capable of producing similar results. As yet, this is not the case in the centrifuge community.

Response by Dr. Kutter:
Centrifuge equipment is developed in different sizes and shapes. He felt that it would be difficult to standardize centrifuges and equipment. Specifically, specialized equipment like shakers.

Response by Dr. Dobry:
He thought that Dr. Kutter's comments were dangerous in that we should not expect to get different results for the same test. It is absolutely necessary for the community to be repeatable in its experiments.

Response by Dr. Phillips:
Commented that Japan has started some work in standardizing testing, but they don't want to stifle creativity.

Response by Dr. Hynes:
She commented that codes would ensure similarity and reduce extreme differences in design. She felt that there was a need to take a closer look at the combination of time, frequency and energy in earthquake/shake tables to refine/define the loads applied. This would be a significant step.

Question by Dr. Zimmie:
He asked the group about the use of centrifuges for educational purposes. For example, their use in classes for illustrating simple design problems.

Response by Dr. Ko:
The University of Colorado has three centrifuges. One is used specifically used for undergraduate classes. He cited some examples of teaching uses.

Response by Dr. Culligan:
She commented that M.I.T. has used the centrifuge for several years in geotechnical classes. Students don't actually use the centrifuge, but they do analyze test data.

Response by Dr. Zimmie:
RPI uses the centrifuge only for demonstrations for the students.

Comment by Dr. Phillips:
There is a need to expand the client base for the centrifuge community. Clients need to see the centrifuge as a worthwhile design tool. The community needs to educate practitioners on the cost and usefulness.

Comment by Dr. Gran:
The centrifuge community needs to demonstrate fidelity to the consumer, show how it works, the benefits and the applicability.

Question by Dr. Schaminee:
He asked if anyone had done any research in engineered caps to deter/defer water? Subsiding landfills? Seismic stability of landfills?

Response by Dr. Culligan:
She commented that 1g tests had been done to look at caps and subsidence.

Response by Dr. Stone:
He commented that he was aware of research on deformation of liners (base and cap) possibly at the Auburn University. That work may be referenced in Centrifuge '91. It involved the use of soils with particle sizes ranging from gravel to bentonite, placed dry and allowed to expand, becoming impermeable.

Various people commented on research areas pertaining to ice ridges as it relates to contaminant spills in frozen soils; specific uses of the centrifuge in extreme climate changes such as global warming; stability of land masses, beach erosion, melting of permafrost, and iceberg scour.